

TITLE OF THE INVENTION

Apparatus for Sealing and Restraining the Flexible Pressure Boundary
of an
Inflatable Spacecraft

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to the field of seal and restraint systems for the establishment of a pressure boundary on inflatable or expandable structures in a vacuum environment. In particular, the present invention relates to the establishment of a pressure boundary between the flexible and the rigid materials of construction utilized on inflatable spacecraft such as orbiting satellites, space stations, and space vehicles, or any other type of space habitat.

2. Discussion of the Prior Art

Inflatable structures for use in space applications utilize flexible, non-rigid materials of construction to develop and maintain an inflatable pressure boundary over a substantial portion of their structure. Augmenting these non-rigid materials of construction are rigid materials that are necessary to form such components as hatches and docking mechanisms. A long-standing problem has been the development of a means to connect the non-rigid, flexible materials of construction

to the spacecraft's rigid structural components to establish a substantially air tight pressure boundary. Compounding this problem is the lack of any single material that has both the requisite gas impermeability, and the strength needed to withstand internal pressurization forces.

Because of a lack of a single suitable material, both a gas membrane and a restraint layer are required to establish an effective pressure boundary. The gas membrane is interior to the restraint layer and is typically a polymeric sheet material. This polymer is substantially impermeable to atmospheric gases to minimize air leakage into space. The restraint layer carries and distributes the internal pressurization loads imposed by the gas membrane.

The prior art has been unable to develop a fully satisfactory method to effectively establish a pressure seal between a flexible pressure barrier and a rigid component. It is the connection of the gas membrane and the restraint layer to the spacecraft's rigid structural components that has proven to be problematic. The best that the prior art has been able to accomplish is the development of a vise like connection mechanism that clamps both the gas membrane and the restraint layer to the rigid structural components of the spacecraft.

This prior art connection has several shortcomings that prevent the full and economic utilization of inflatable spacecraft. One of the most significant deficiencies is that the clamp mechanism must exert tremendous compressive force on the restraint layer and the gas membrane. This compressive force is necessary to resist

the pull out forces caused by the spacecraft's internal pressurization. These pull out forces in turn create shear stresses in both the restraint layer and the gas membrane.

The gas barrier, because of the special polymeric sheet materials needed to prevent air leakage, is generally thin, delicate, and prone to a variety of stress failure mechanisms. The clamp compressive forces and the induced shear stresses are sufficient to distort and damage not only the gas membrane, but also the restraint layer. Although the restraint layer is made from very strong materials, the threads from which these fabrics are woven can still be damaged by the clamp mechanism. Because of these compressive and shear forces, the load rating of the restraint layer is degraded. Consequently, the prior art vise like clamping mechanism is a poor method for connecting the gas membrane and restraint layer to the spacecraft's rigid structural components.

In addition to the clamping stresses that are directly imposed on the gas membrane, the restraint layer itself induces stresses in the gas membrane. As noted above, the prior art clamps the restraint layer and gas membrane together in a vise like grip. This causes the restraint layer and the gas membrane to act like a single component. This results in the transfer of forces from the restraint layer to the gas membrane. The interface of the highly stressed restraint layer with the gas membrane can cause a failure several ways.

The first failure mode results from the transfer of tensile forces in the restraint layer to the gas membrane, causing the gas membrane to be placed in tension. This tensile

74 stress further induces shear stresses in the gas membrane because of the restraint
imposed by the clamp. The gas membrane can then fail in either tension or shear.

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The gas membrane may also fail as a result of fatigue. Constantly fluctuating
78 spacecraft air pressure can cause alternating stresses in the restraint layer that are
transferred to the gas membrane. The constant movement of the restraint layer
80 against the gas membrane may cause fatigue failure of the gas membrane. The gas
membrane may also fail due to abrasion caused by the relative movement of the
82 restraint layer against the gas membrane.

84 Another problem with the prior art design relates to the effectiveness of the air seal
created by the clamping mechanism and the gas membrane. Because both the gas
86 membrane and the restraint layer are clamped together, (back to back against an o-
ring) sufficient compressive forces may not be available to ensure a leak tight seal.
88 This is a result of the relatively thick, deformable nature of the restraint layer and its
susceptibility to creep under a compressive load. Because of deformation and creep,
90 the restraint layer continues to flow away from the location of the imposed
compressive force. Consequently, the compressive force against the o-ring is
92 gradually reduced, and the hermetic seal is degraded or lost.

94 Internal air pressurization further contributes to seal degradation. Internal air
pressure works between the gas membrane and the o-ring, urging the gas
96 membrane off the o-ring and reducing the effectiveness of the seal. Compounding
this problem is the potential for the development of wrinkles in the restraint layer
98 fabric. These wrinkles may propagate over the gas membrane and the o-ring seal.

Air pressure may then force the gas membrane off the o-ring and into the wrinkled area of the restraint layer, thus forming an air leakage pathway.

A similar prior clamping connection is shown for an inflatable lunar habitat as discussed in "Deployable Lunar Habitat Design and Materials Study, Phase I Study Program Results", developed for the NASA Johnson Space Center. The inflatable habitat discussed in the NASA report differs from the present invention in at least one other profound respect. The habitation has a fixed, unexpandable diameter that only allows axial expansion.

The inability of the prior art design to expand diametrically severely restricts the principal advantage of inflatable spacecraft technology. That is, the ability to minimize the volume of the launch package, and maximize the deployed inflated volume. In fact, the diameter of the launch vehicle is generally the limiting dimension for almost all launch payloads. The inability to utilize the prior art to obtain an expansible diameter is an additional handicap that undermines the development of inflatable spacecraft. Consequently, a new connection mechanism is needed to provide an inflatable spacecraft with an expansible diameter.

In summary, the prior art designs are inadequate to provide a reliable and effective pressure boundary. As noted above, the prior art seal and restraint system subjects the restraint layer and the gas membrane to excessive stresses that can damage either or both of these components and result in structural failure. The prior art also allows excessive air leakage losses between the gas membrane and the o-ring. Furthermore, the prior art does not allow the gas membrane layer to be replaced

124 without disassembling the restraint layer. For all of these reasons, the prior art
design is inadequate, and a new sealing and restraint system is needed to make
126 inflatable space structures economical and reliable.

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SUMMARY OF THE INVENTION

130 The present invention provides a novel apparatus for establishing an effective seal and
restraint system that can anchor a flexible pressure boundary to the rigid structure of an
132 inflatable spacecraft. The importance of the present invention is that it can establish a
substantially hermetic seal between a flexible pressure boundary and a rigid structure
134 with sufficient strength to allow the spacecraft to operate in a vacuum while internally
pressurized.

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138 The present invention establishes a pressure boundary using both a restraint layer and a
gas membrane that cooperatively act to seal and restrain the pressure boundary to the
spacecraft's rigid structural components. No significant tensile stresses are imposed on
140 the gas membrane because it is oversized and located inside the restraint layer volume
in which it is constrained.

142
144 The present invention uses separate attachment connections for the gas membrane and
the restraint layer. The separation of these two attachment mechanisms isolates the
sealing system from the restraint system, while at the same time allows the gas
146 membrane to interact with the restraint layer over the remainder of the gas membrane
surface area.

148
150 The gas membrane attachment mechanism establishes a substantially air tight seal,
while imposing negligible stresses on the gas membrane. This has been accomplished
using a free floating compression seal, which traps the gas membrane between at least

one elastomeric seal (e.g., o-ring seals) and a flange, or preferably, between a pair of elastomeric seals. The only forces exerted on the gas membrane are the compression stresses at the seal contact point. This seal isolates the gas membrane from tensile stresses while providing a very effective pressure seal. This allows the gas membrane to float between the seals, thereby preventing any significant stresses from developing on the gas membrane.

The restraint layer attachment mechanism prevents crushing of the restraint layer and minimizes stress concentration factors while evenly distributing the restraint layer loads to the spacecraft's rigid structural components. Loops at the ends of the restraint layer transfer internal pressurization loads to a retaining member in the rigid spacecraft structure. The restraint layer loops are free to pivot about the retaining member to minimize stresses on the loops and the restraint layer. If desired, an anti-chafing protective sleeve can be placed over the loop to prevent abrasion damage to the restraint layer loops. The retaining member itself is trapped between two flanges that allow the retaining member to evenly transmit the restraint layer forces into the mating flanges.

From the brief summary provided above it can be seen that the present invention provides many advantages over the prior art and has the following specific objects:

One of the objects of the present invention is to provide a substantially leak tight seal between the gas membrane and its connection point to the spacecraft's rigid structural components without unduly stressing the gas membrane. This has been accomplished using a free floating compression seal.

Another object of the present invention is to provide a more effective air seal by eliminating the restraint layer to gas membrane interface found in the prior art. The present invention eliminates this interface, establishing two separate anchoring mechanisms for the gas membrane and the restraint layer.

Another object of this invention is to minimize mechanical damage to the restraint layer at the connection point to the rigid structure. This has been accomplished in the present invention using a plurality of restraint loops placed around a retaining member held in place by a flange assembly.

In summary, the present invention minimizes air leakage, maximizes gas membrane service life, minimizes stresses imposed on the gas membrane and restraint layer, provides a diametrically expansible structure, and allows the gas membrane to be replaced without removing the restraint layer. These are all significant technical advancements over the prior art. The technological advancements of the present invention substantially increase the commercial viability of inflatable spacecraft.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross sectional view of the pressure barrier seal and restraint apparatus.

FIG. 2 is an isometric view of the pressure barrier seal and restraint apparatus.

FIG. 3 is an exploded isometric view of the pressure barrier seal and restraint apparatus.

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DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

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Preferred embodiments of the present invention that illustrate the best modes now
contemplated for placing the invention in practice are described as follows, and in
conjunction with the attached drawings that form a part of this specification. The
preferred embodiments are described in detail without attempting to show all of the
various forms and modifications in which the present invention may be embodied. The
preferred embodiments described are illustrative, and as will become apparent to those
skilled in the arts, can be modified in numerous ways within the spirit and scope of the
invention, the invention being measured by the appended claims and not by the details
of the specification.

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The present invention is a restraint and sealing system for use in inflatable space
structures that utilizes a flexible, non-rigid pressure boundary. Examples of the
construction techniques utilized in the development of these inflatable space structures
is provided in Deployable Lunar Habitat Design and Materials Study, Phase I Study
Program Results”, developed for the NASA Johnson Space Center, under Purchase
Order #T-357-5V, hereby incorporated by reference. FIG. 1, FIG. 2, and FIG. 3 depict
the present invention with the seal and restraint system, as it would be installed in a
typical inflatable spacecraft. The present invention utilizes a gas membrane 60 and a
restraint layer 50. The gas membrane provides an air seal against the vacuum of space.
The restraint layer contains the internal pressurization forces created by the pressure
differential between the vacuum of space and the space structure’s internal pressure.

226 The gas membrane and the restraint layer work, function, and interact cooperatively to
form the pressure boundary of the spacecraft.

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The gas membrane 60 is typically composed of polymeric sheet material, and is inside
230 the restraint layer volume. The gas membrane is independently attached to the rigid
spacecraft structure between a seal flange 10 and the base flange 20 to establish a
232 substantially hermetic seal. The gas membrane is oversized so that its fits loosely inside
the restraint layer 50. This allows the gas membrane to expand against the restraint
234 layer 50, transferring the internal pressurization forces to the restraint layer. This
configuration minimizes tensile and shear loads on the gas membrane. Although this
236 places the gas membrane in compression, as with most materials, polymeric materials
are able to withstand compressive forces quite readily. This load configuration is
238 critical, because the gas membrane is generally thin and delicate. Consequently, the gas
membrane must be fully supported over its entire surface area to prevent its extrusion
240 through the restraint layer.

242 To ensure that the gas membrane 60 is not extruded through the restraint layer 50, some
restraint layer designs may require a carrier layer 52. The carrier layer is preferably
244 attached to the restraint layer, although it may be attached to the gas membrane, or
simply placed between the gas membrane and the restraint layer. The carrier layer 52
246 covers any voids or discontinuities that may be present in the restraint layer. The
carrier layer 52 prevents the extrusion of the gas membrane and provides the added
248 benefit of providing a smoother surface for the gas membrane to push against,
minimizing stresses and abrasion on the gas membrane.

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252 In the preferred embodiment, the gas membrane 60, to be fully protected from the hard
surfaces at the attachment point, is sandwiched between elastomeric seals, such as o-
254 rings 61, 62. These o-rings may ride in a groove provided on the mating face of the seal
flange and the second face of the base flange. These o-rings substantially isolate the gas
256 membrane from potentially damaging attachment point stresses. The only stresses
imposed by the o-rings are compressive stresses on the trapped portion of the gas
258 membrane. It is this compression seal that provides a substantially airtight seal
between the rigid spacecraft structure and the gas membrane. If desired, to simplify the
260 design of the sealing system, a single seal may be used to trap the gas membrane
between the seal and either the mating face of the seal flange 10 or the second face of the
262 base flange 20. This configuration although simpler, has the potential for significantly
more wear on the gas membrane.

264 Normally, the internal pressurization forces the gas membrane to conform against the
266 restraint layer, preventing the gas membrane from slipping out from between the seals.
A deadman may be used, if desired, to ensure that the gas membrane is not accidentally
268 pulled from between the o-ring seals. This feature provides positive backup to prevent
the possible retraction of the gas membrane from between the seals.

270 The deadman 63 may be formed by doubling the gas membrane 60 to form a
272 substantially thicker portion at the edges of the gas membrane. This increased
thickness may be heat sealed, sewn, or otherwise maintained in place. Alternately, a
274 rigid member may be attached to the gas membrane 60 to form the deadman. The
deadman may be placed in the cavity 11 formed between the mating face of the seal

276 flange 10 or the second face of the base flange 20. Although the deadman 63 fits into
cavity 11, it cannot be extruded because the deadman is larger than the clearance
278 between the base flange 20 and the seal flange 10.

280 The restraint layer 50 is typically made from polymeric materials such as Kevlar or
Vectran. These materials are typically woven to provide a high strength, yet flexible
282 material. The restraint layer may take many different forms and shapes. For example,
the restraint layer may be made from sheet materials, straps, or formed using a basket
284 weave type construction. The restraint layer may take on any form, use any type of
construction, or be made from any material, provided that the restraint layer has the
286 ability to be expand from a collapsed position into a fully deployed position when
inflated.

288
The restraint layer 50 is connected to the rigid spacecraft structure to form an enclosure
290 within which the gas membrane is contained. The restraint layer, in a substantially
cylindrical structure, experiences stresses that are essentially equivalent to the standard
292 hoop, axial, and shear stresses associated with any cylindrical pressure vessel. The
restraint layer must be connected to a rigid structure in a way that allows the stresses to
294 be evenly and uniformly distributed, throughout the restraint layer as well as the rigid
structure.

296
To uniformly distribute the internal pressurization forces, the present invention utilizes
298 a retaining member 40. The retaining member is held in place with a base flange 20 and
a locking flange 30. The first face of the base flange 20, in conjunction with the mating
300 face of the locking flange 30, contact to create a series of recesses 23. The recesses 23

extend from under the retaining member, and exit through the outer surface around the
circumference of the base flange 20 and the locking flange 30 at their interface. Located
between each of these recesses is a passage 24 that connects to, and is in communication
with each adjacent recess. These passages are for capturing the retaining member 40.

Connected to the restraint layer 50 is a plurality of loops 51 that are attached at one end
to the restraint layer, and at the other end attached to the retainer member. The
restraint layers loops 51 fit inside the recesses and extend around the retaining member
40. The restraint layer loops uniformly distribute the stresses in the restraint layer to
the retaining member. The retainer member, by virtue of its continuity around the
mating flanges distributes the restraint layer loads uniformly around and into the rigid
structure. The retaining member and enclosing flanges minimize abrasion, fatigue, and
stresses on the restraint layer 50 or the restraint layer loops 51.

Even with the carrier layer, additional protection for the gas membrane may be
desirable at the point where the restraint layer loops enter their respective recesses. To
ensure that the gas membrane is not pinched between the loops and the flanges, or
otherwise extruded between the loops, a dam 65 may be placed around the outer
circumference of the base flange, between the restraint layer and the gas membrane.
The dam 65 may be captured in a groove around the base flange. Alternately, bolt hole
recesses around the circumference of the base flange may be used to hold the dam. This
provides the further benefit of protecting the gas membrane from the discontinuities
presented by the bolt heads.

The dam diverts the gas membrane away from the recesses and prevents the extrusion
of the gas membrane. The dam is preferably made from a compressible elastomeric
material, allowing the force of the gas membrane to compress the dam against the
restraint layer. The conformance of the dam to the restraint layer ensures the
elimination of any spacing between the dam and the restraint layer, preventing the
pinching or extrusion of the gas membrane.

The retaining member **40** itself may be formed from separable components to allow the
loops in the restraint layer to be preformed, ready for assembly. During assembly, the
restraint layer loops are placed around the retaining member, and the retaining member
may be assembled into a single component. The retaining member **40** is in turn placed
between the base flange **20** and the locking flange **30**. The locking flange and the base
flange are connected together to trap the retaining member. Similarly, the seal flange
and the base flange are connected together to form the compression seal holding the gas
membrane. The entire assembly may then form an opening for a spacecraft hatch,
bulkhead, or docking mechanism.

Although it is not necessary, the flange assembly (base flange, the locking flange, and
the seal flange) may be further attached around a rigid member **100** to build upon the
spacecraft's structure. The rigid member **100** may be hollow to provide access for a
hatch, docking mechanism, or view port. Alternately, the ends of the base flange **20**
may be extended to take the form of rigid member **100**. However, neither the rigid
member, nor extension of the base flange is necessary, and only represent different
embodiments of the present invention with greater structural rigidity.

350 In summary, the present invention described herein provides a very low leakage seal
and restraint system that can be used to establish and maintain the pressure boundary
352 around an inflatable spacecraft. Although the present invention has been described
above with reference to certain preferred embodiments, it is understood that
354 modifications and variations are possible within the scope of the appended claims that
follow. Among these variations is the potential to use the present invention to affix the
356 pressure boundary using a single retainer member to form a single opening in the
flexible pressure boundary. Alternately, multiple retainer members may be used to
358 form any number of openings for hatches, docking mechanisms, or viewing ports.